Muon-Electron Conversion (μ2e) at FNAL

R. Bernstein
FNAL

NP'08

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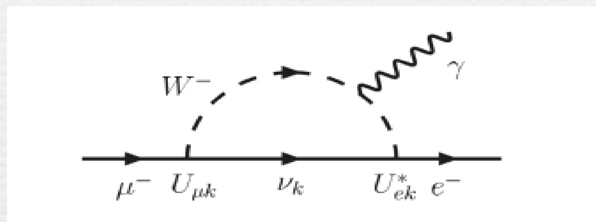
many MECO collaborators with considerable knowledge

Motivation

- ν's have mass! Therefore individual lepton numbers are not good quantum numbers

- Therefore occurs in Charged Leptons as well



- Except neutrinos have to change flavor in loop...

$$\mathrm{BR}(\mu \to e\gamma) \quad = \quad \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54} \quad ☹$$

- But this is good! New physics not hidden by boring old neutrino oscillations

Major Contributions

Standard Model SuperSymmetry

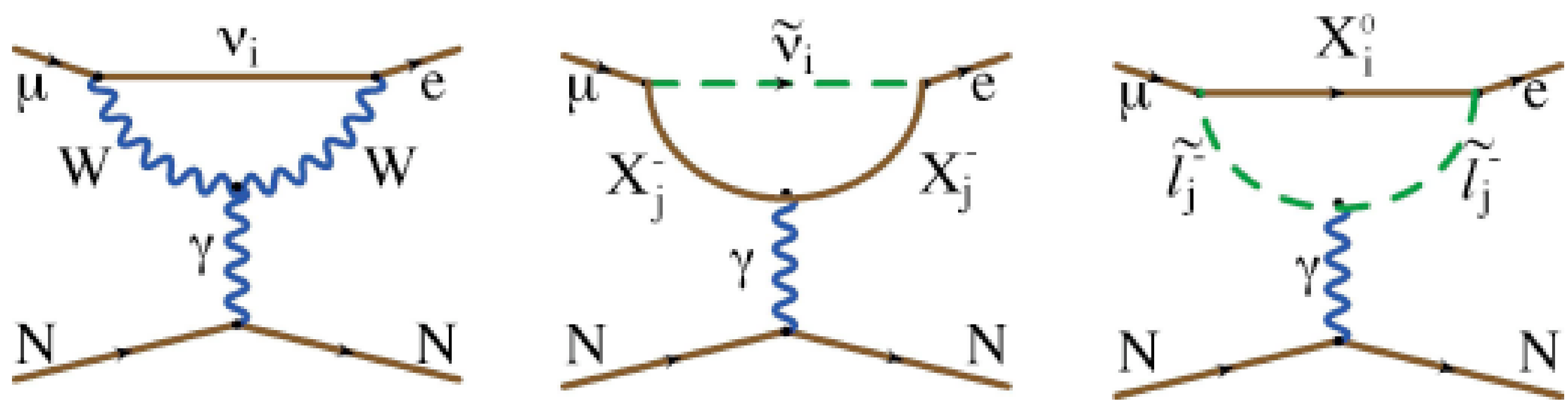
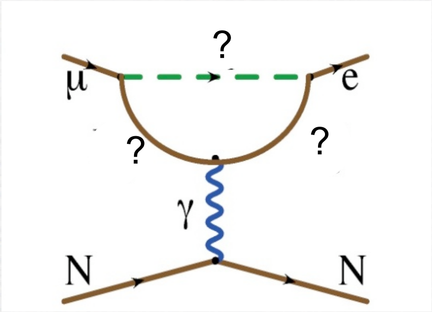


Figure 1.1: The leading Standard Model diagram for μ+N → e+N is shown on the left. The center and right figures are the dominant SUSY diagrams.

- Supersymmetry, for example: far better than $\mu \rightarrow e\gamma$
- Far Higher than LHC, > 1000 TeV

μe Conversion and $\mu\to e\gamma$

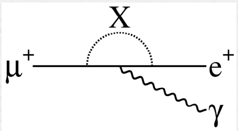
- *Dipole/Penguin*



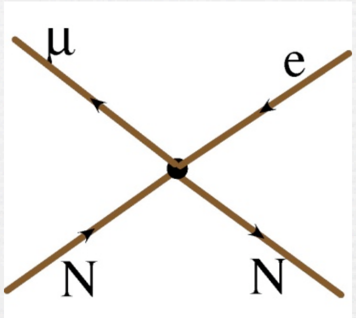
κ

- This type of diagram gives rise to small CLFV through virtual neutrino mixing

- Also contributes to μ→eγ if photon real



- *Fermi Interaction*



Λ

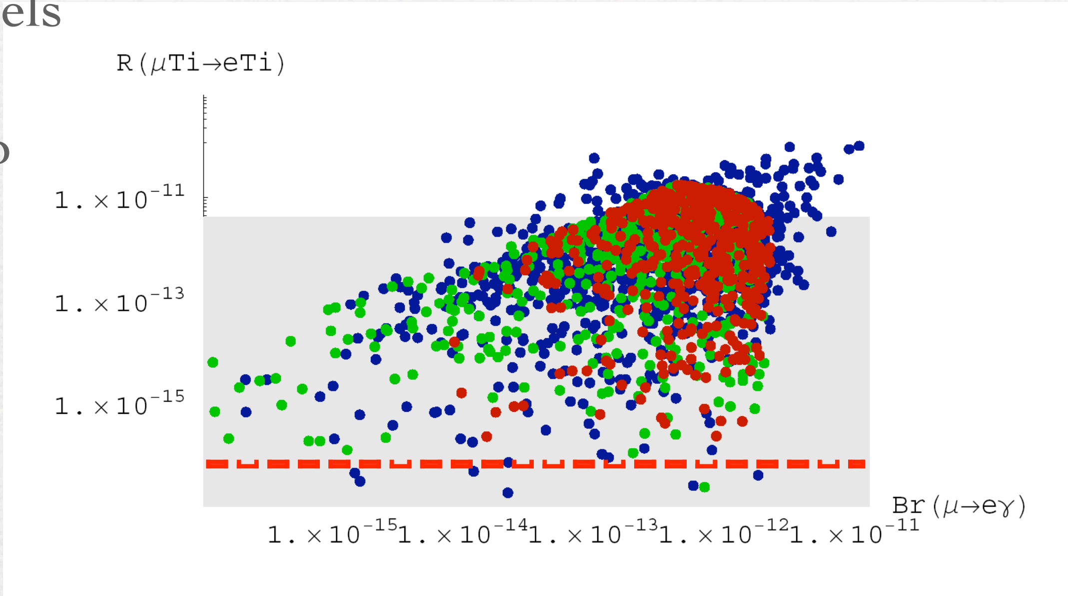
- Corresponds to exchange of a new, massive flavor-changing neutral current particle $\frac{1}{\Lambda^2} = \frac{f^2}{16\pi^2}\frac{1}{M^2_{\rm new}}$

- ***Does not produce μ→eγ***

$$L_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

Combination of μe Conversion and $\mu \rightarrow e\gamma$

- Distinguish by using both: sample Little Higgs Models
- Compare and Contrast to LHC
- **Measuring in several channels in several experiments is always better!**

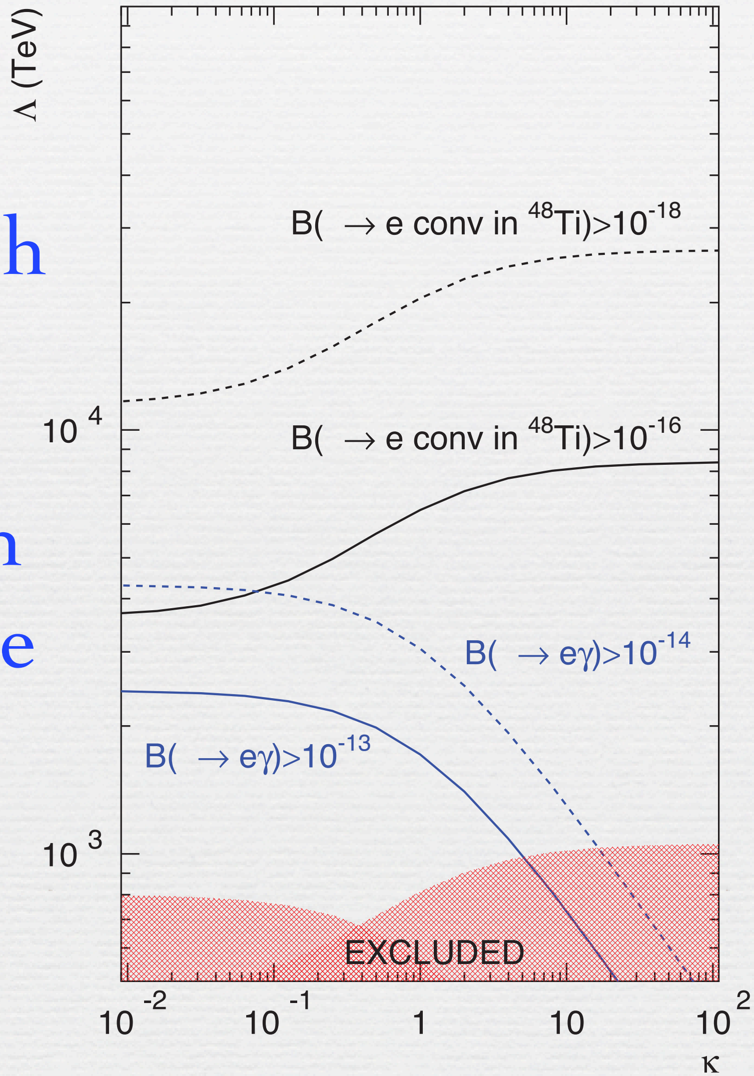


$\mu \rightarrow e\gamma$ conversion in Ti vs $\mu \rightarrow e\gamma$ for Randall-Sundrum, Agashe et al.,

Overview of Reach

André de Gouvêa, Project X Workshop Golden Book

Two Points:
1) Mass Reach of 10^4 TeV
2) More Powerful than $\mu \to e\gamma$ because of FCNC Λ capability



higher mass scale

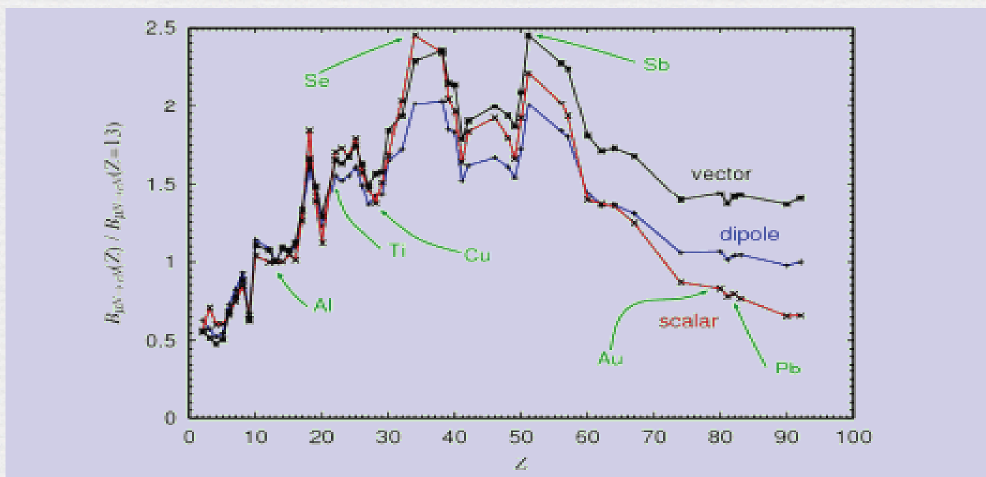
Λ four-point, κ penguin

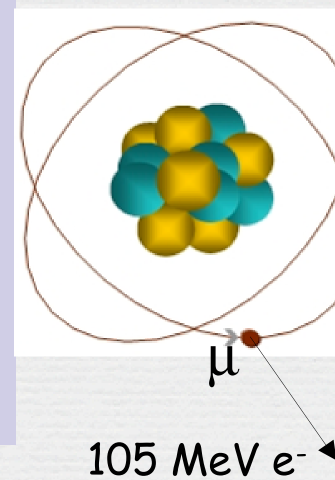
What Do We Measure?

- μ to e conversion in the field of a nucleus

$$R_{\mu e} \equiv \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1))}$$

- *Stop muons in target*
- Physics sensitive to Z: with signal, can switch target to probe source of new physics





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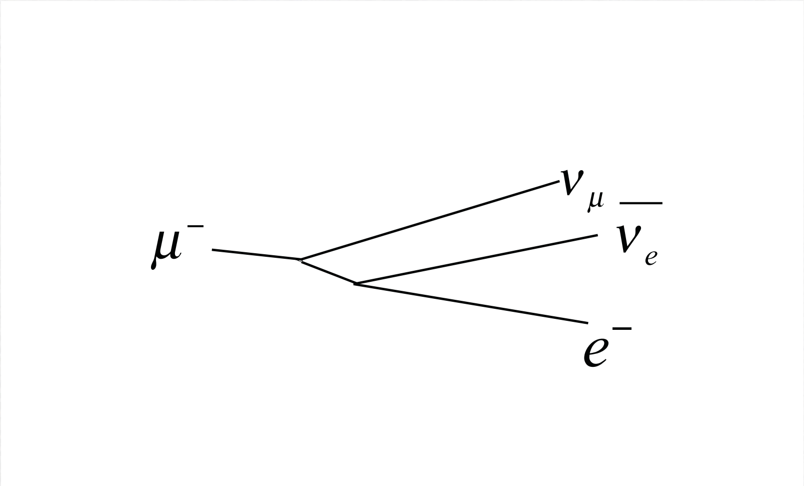
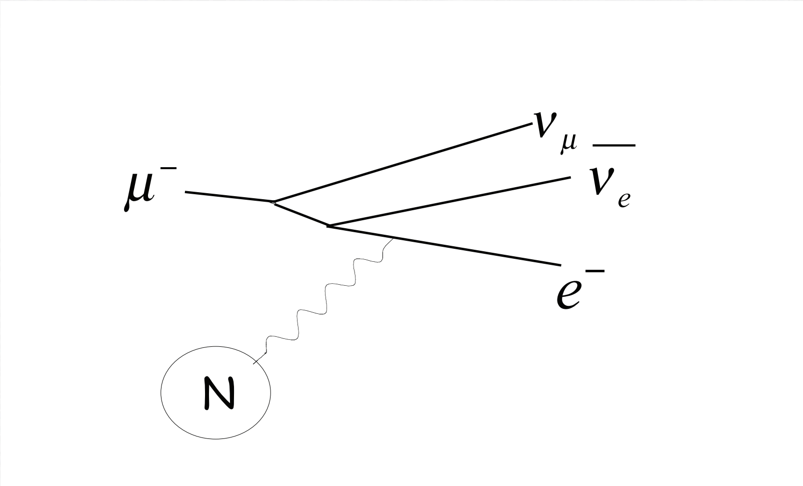
Backgrounds

- Decay-in-Orbit and Misreconstructions
  - resolution and redundancy
- Prompt, Beam Related
  - extinction, delayed live window
- Cosmic Rays
  - shielding

Decay-in-Orbit Background



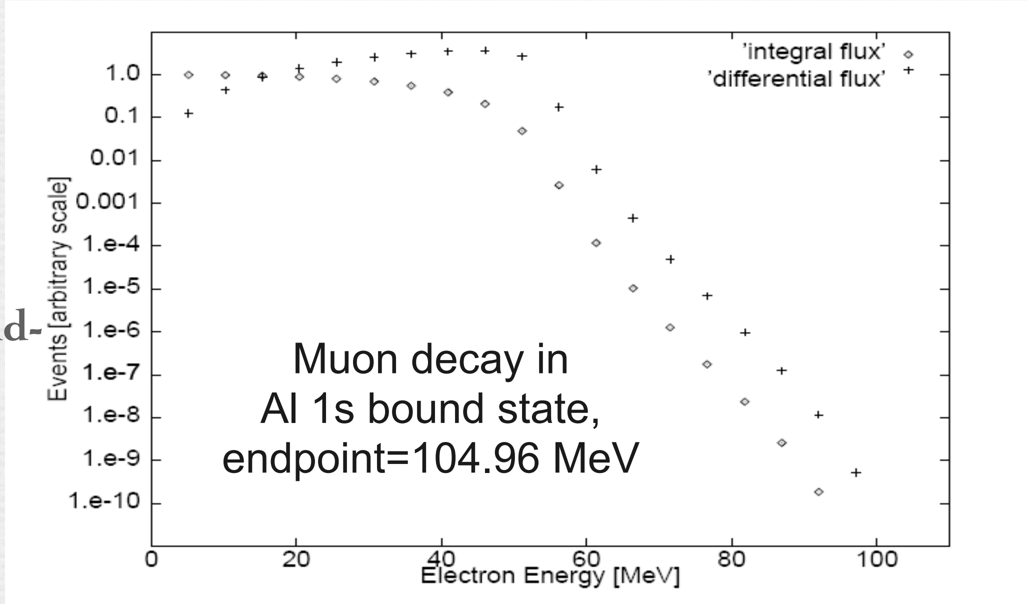


- High Rate
- Peak 52 MeV
- Detector *insensitive* to these
- Coherent balance of momentum
- Rate falls as $(E_{max} - E)^5$
- Drives Resolution

Decay-In-Orbit Details

- Ee(max)= ($m_\mu c^2$ - NuclearRecoilEnergy -AtomicBindingEnergy)
- For Z=13 (Al), Atomic BE=0.529 MeV, Recoil energy=0.208 MeV → Ee(max) =104.96 MeV
- Rate near the maximum energy falls very rapidly. Near endpoint: proportional to $(Ee(max)-E)^5$
- **Major potential source of background- Discriminate against it with good electron energy resolution, ~1 MeV FWHM for μ2e**

looks exactly like signal except for electron energy

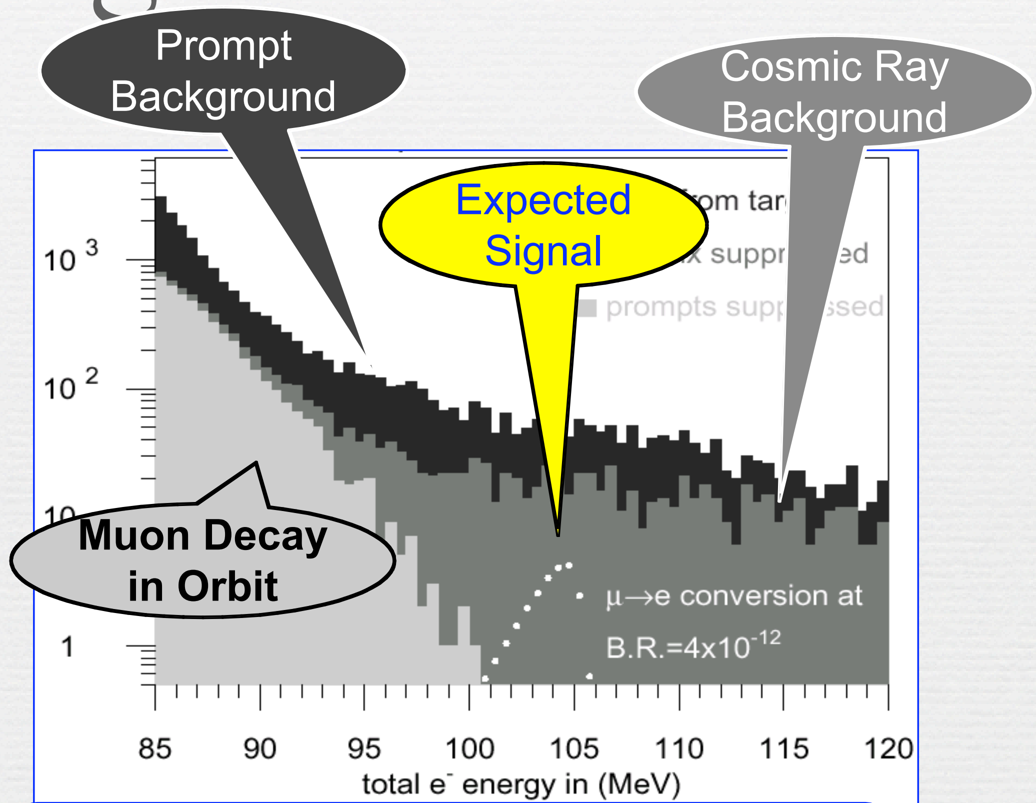


Prompt Backgrounds

- Prompt: due to beam particles – which interact almost immediately when they enter the detector region,
  - Radiative pion capture, $\pi^- + A(N,Z) \to \gamma + X$.
    - $\gamma \to e^+e^-$; if one electron ~ 100 MeV in the target, looks like signal. Major limitation in SINDRUM II.
  - Beam electrons: incident on the target and scatter into the detector region. Need to suppress e^- with E>100 MeV near endpoint
  - In-flight muon decays

Existing Limits

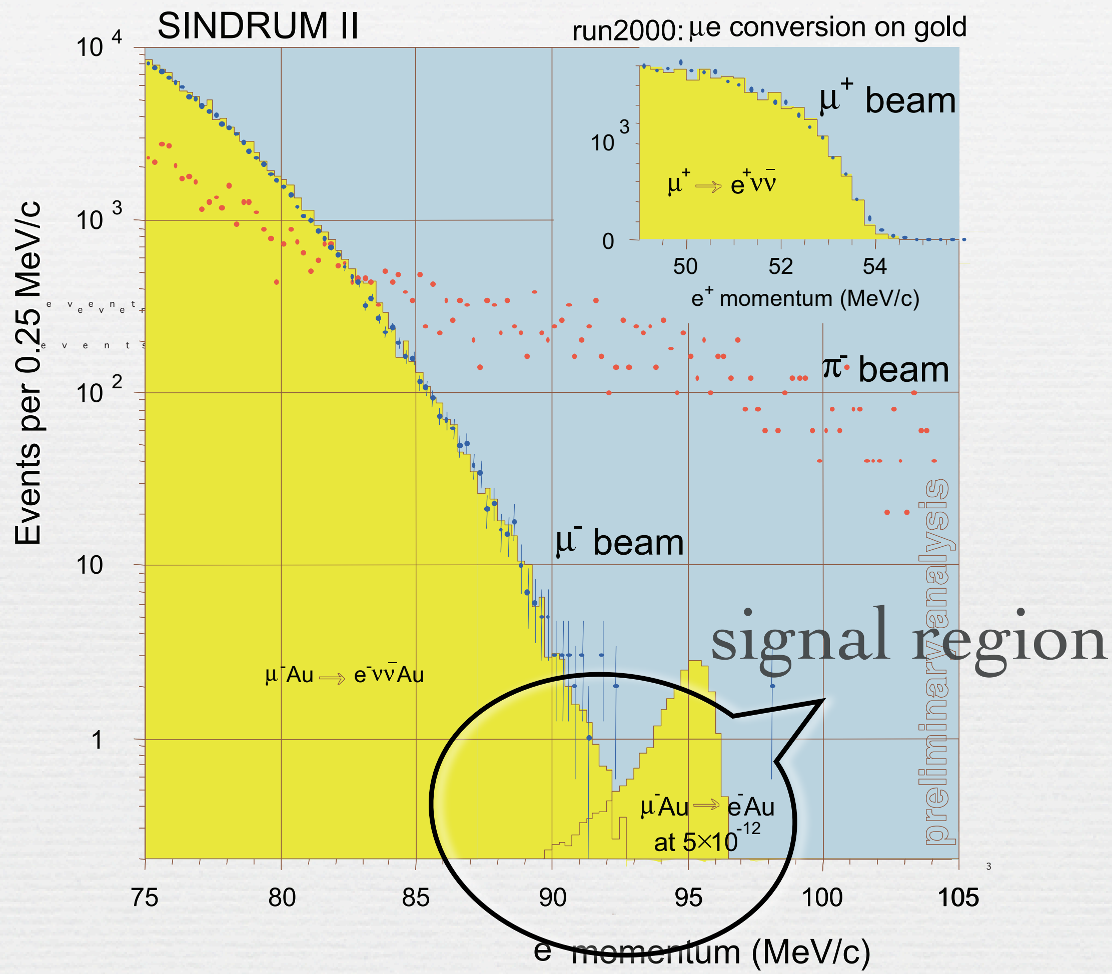
- $R_{\mu e} < 6.1 \times 10^{-13}$ in Ti (SINDRUM)
- Want to probe to 10^{-16} or better
- Factor of $\approx 10^4$ improvement non-trivial



Experimental signature is 105 MeV e⁻ originating in a thin Ti stopping target

Scary Plot

- Final SINDRUM-II on Au
- Note Background in Signal Region
- Multiply Problems by 10^4



July 14, 2001

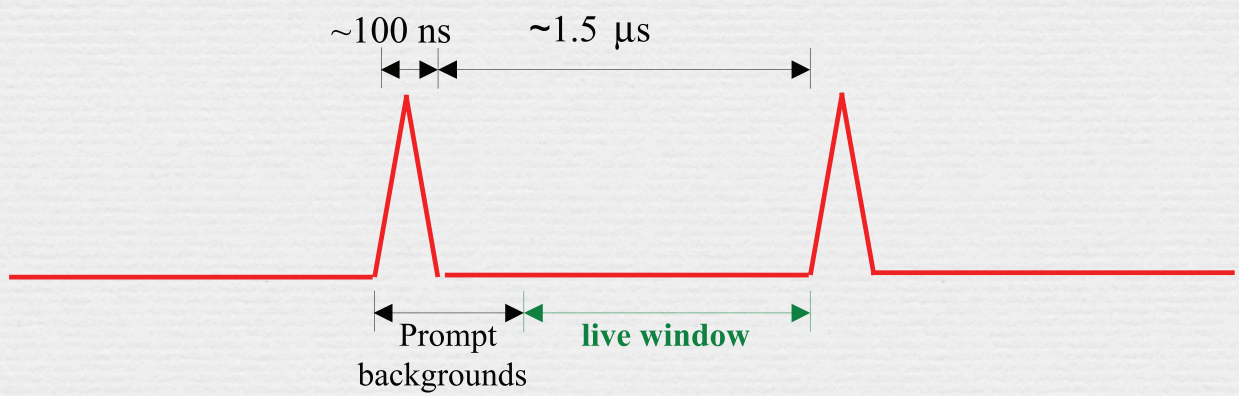
HEP 2001 (W.Bertl - SINDRUM II collaboration)

μ2e at FNAL

- Improvements:
  - **>10^3 increase in muon intensity from SINDRUM**
    - High Z target for improved pion production
    - Graded solenoidal field to maximize pion capture
  - **Curved Transport Solenoid and Pulsed Beam to Eliminate prompt backgrounds**
    - must achieve required extinction *and measure it*
  - **Resolution for Decay-In-Orbit Critical**

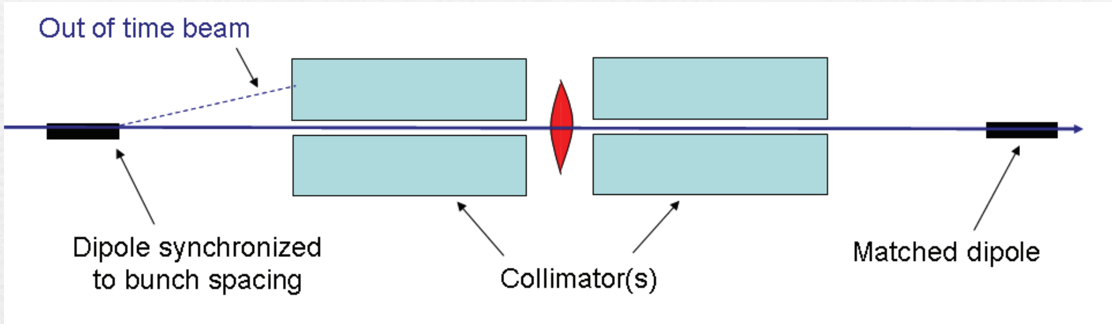
Pulsed Beam

- Beam pulse duration << τ_μ, Pulse separation $\approx \tau_\mu$
- Large duty cycle
- Extinction between pulses < 10^{-9} (assume this for calculations)



Measuring Extinction Rate

- Protons in beam between pulses:



- "Switch" dipole timing to eliminate bunches, accept background for direct measurement

- Other schemes under investigation

  - Measurement: collimators and telescope?

Outline of Remainder

- Beam pre- and post-Project X:
  - how do we get muons to target? how many? time structure?
- Detector:
  - How Do We Achieve Required Rejection and Resolution?

8 GeV Power

20 kW (current)

200 kW (Project X)

2000 kW (Project X Upgrades)

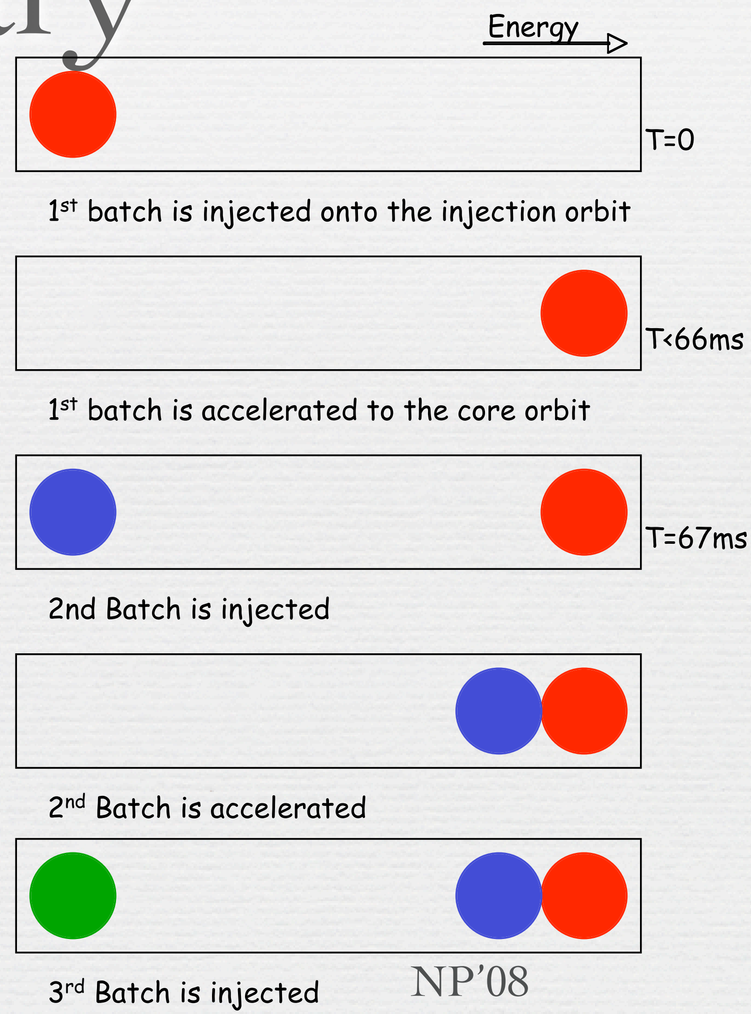
Intensity Summary

point of this slide: if MECO worked, *μ2e* at FNAL works: pre-project X or with Project X

	MECO	Mu2e Booster	Mu2e Project X, no expt. upgrade	Mu2e Project X, expt. upgrade
protons/sec	40×10^{12} (design)	18×10^{12}	70×10^{12}	160×10^{12}
average beam power	**50 kW** (design)	**23 kW**	**90 kW**	200 kW
duty factor	0.5 s on, 0.5 s off, 50%	90%	90%	90%
instantaneous rate	**80×10^{12}** (design)	**20×10^{12}**	**77×10^{12}**	220×10^{12}
short term beam power	**100 kW** (design)	**25 kW**	**100 kW**	220 kW
Beam pulse period, msec	1.35	1.65	1.65	1.65
Data collection time interval msec	0.7-1.35	0.7-1.65	0.7-1.65	0.7-1.65

Quick Fermilab Glossary

- Booster:
  - The Booster accelerates protons from the 400 MeV Linac to 8 GeV
- Accumulator:
  - momentum stacking successive pulses of antiprotons now, 8 GeV protons later
- Debuncher:
  - smooths out bunch structure to stack more $\bar{p}$
- Recycler:
  - holds more $\bar{p}$ than Accumulator can manage, "store" here

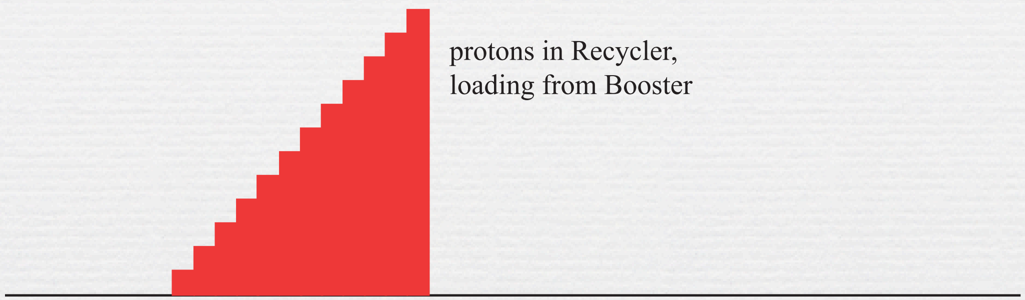


Overall Scheme

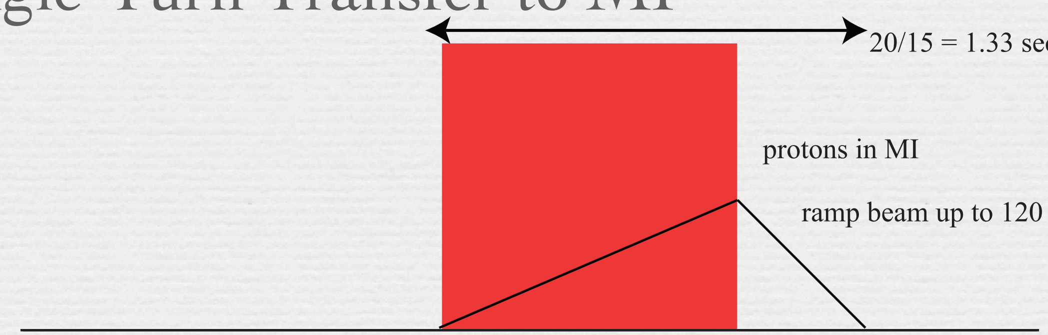
- Now:
  - Booster-MI-Recycler
  - MI is limiting since must load MI fully before accelerating to 120 GeV
- In NovA/μ2e era:
  - Booster-Recycler and slip-stacking
  - Load into Recycler while accelerating in MI
- In Project X Era:
  - Linac-Recycler

NovA Era

- In order to increase protons to the NOvA neutrino experiment after the collider program ends, protons will be "stacked" in the Recycler while the
  - Load from Booster to Recycler

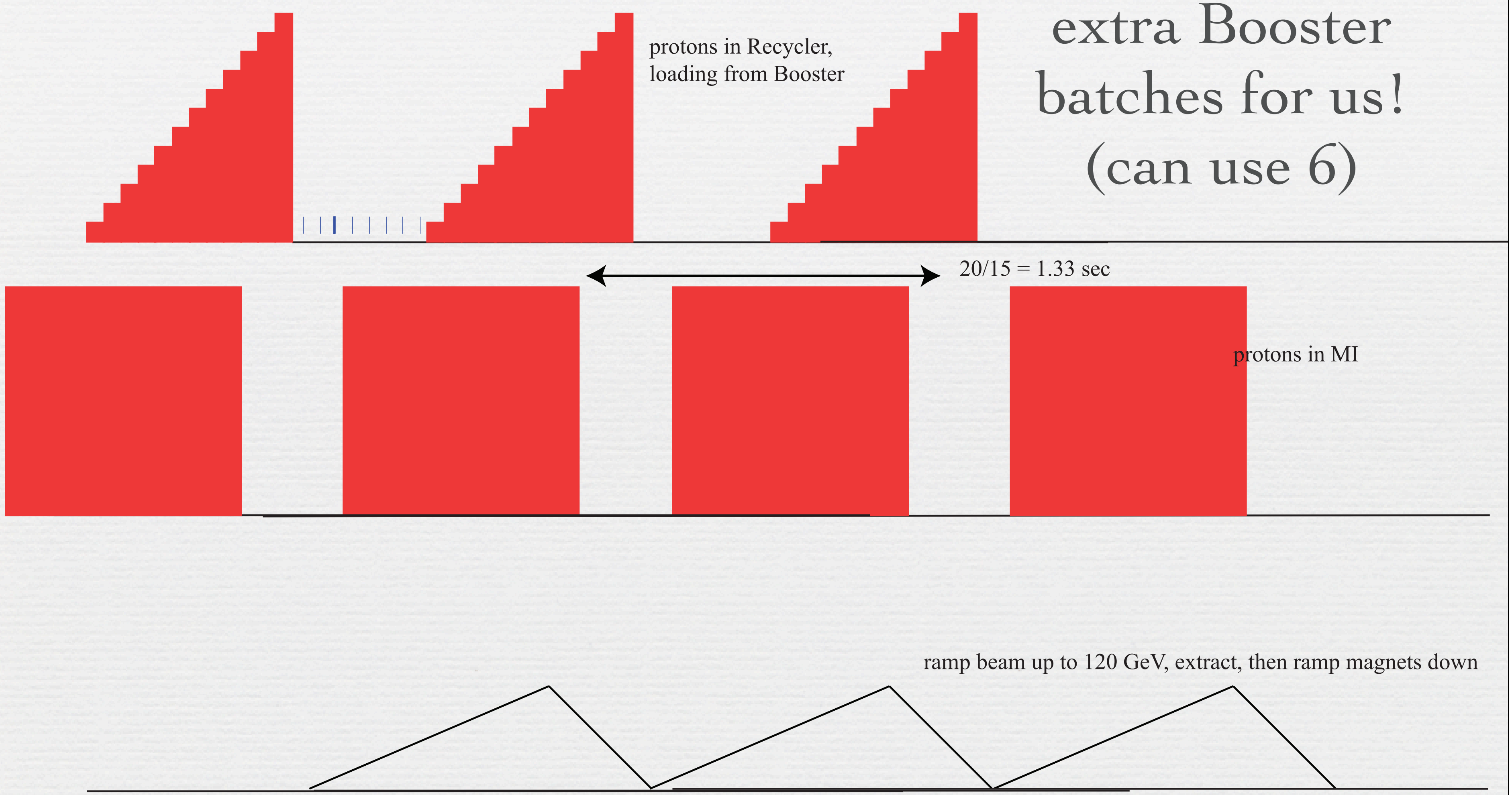


  - Single-Turn Transfer to MI

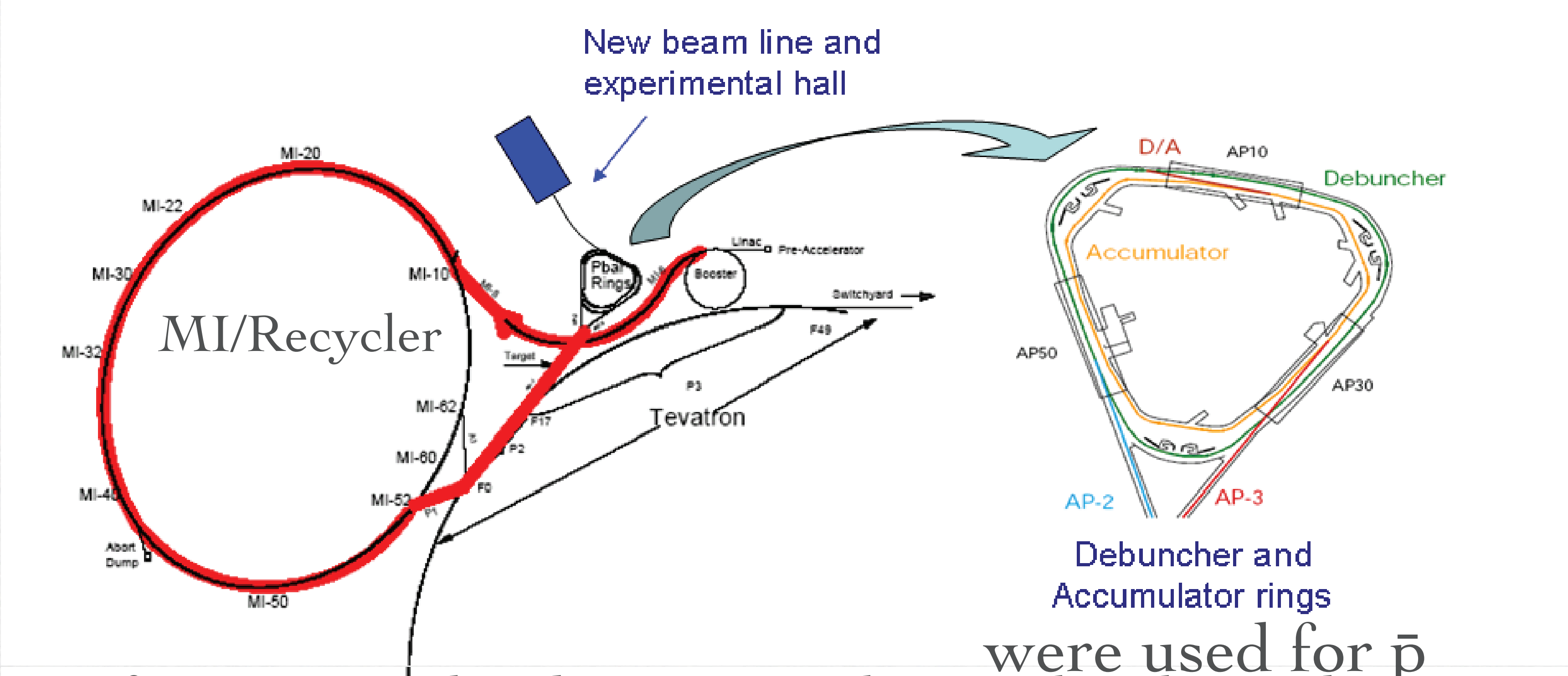


All Together...

can fit eight extra Booster batches for us! (can use 6)



Booster-Era (before Project X)

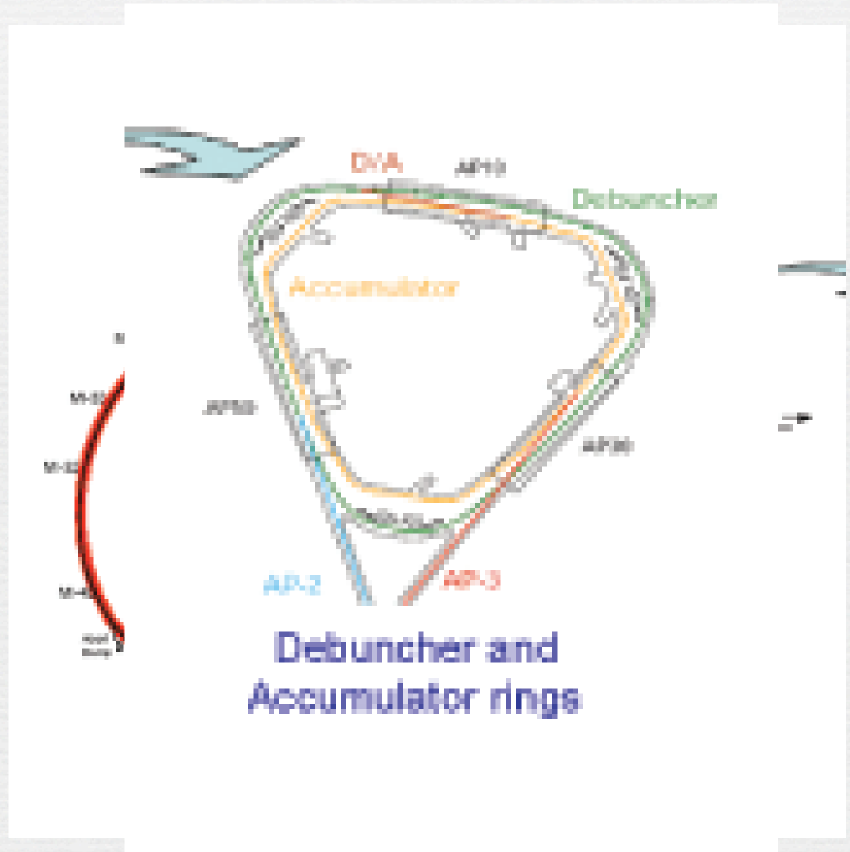


were used for $\bar{p}$

- After TeVatron shut-down, Accumulator, Debuncher, and Recycler "freed" from antiprotons

“Boomerang Scheme”

- Booster Batches transported partway through Recycler and injected directly into Accumulator
- “Momentum-Stack” batches in Accumulator
- Transfer to Debuncher
- Rebunch into Single Bunch:
    - 38 nsec RMS, ±200 MeV
- Resonant Extraction



Numerically,

- can get 8 Booster Batches every 1.33 sec MI cycle, or 4.8E20/yr (4E12/Booster Batch) from Booster
  - currently 10.5 Hz in Booster, need 15 Hz
  - limits of Booster RF and radiation can be overcome with some work to achieve this
- # of batches limited by longitudinal emittance in A/D to 6 of 8 (84 x .038 ev-sec)
  - Assume **3.6E20** = (6/8 × 4.8) in planning
- This manipulation can produce out-of-bucket beam
- ∴ extinction is important: must be controlled and measured

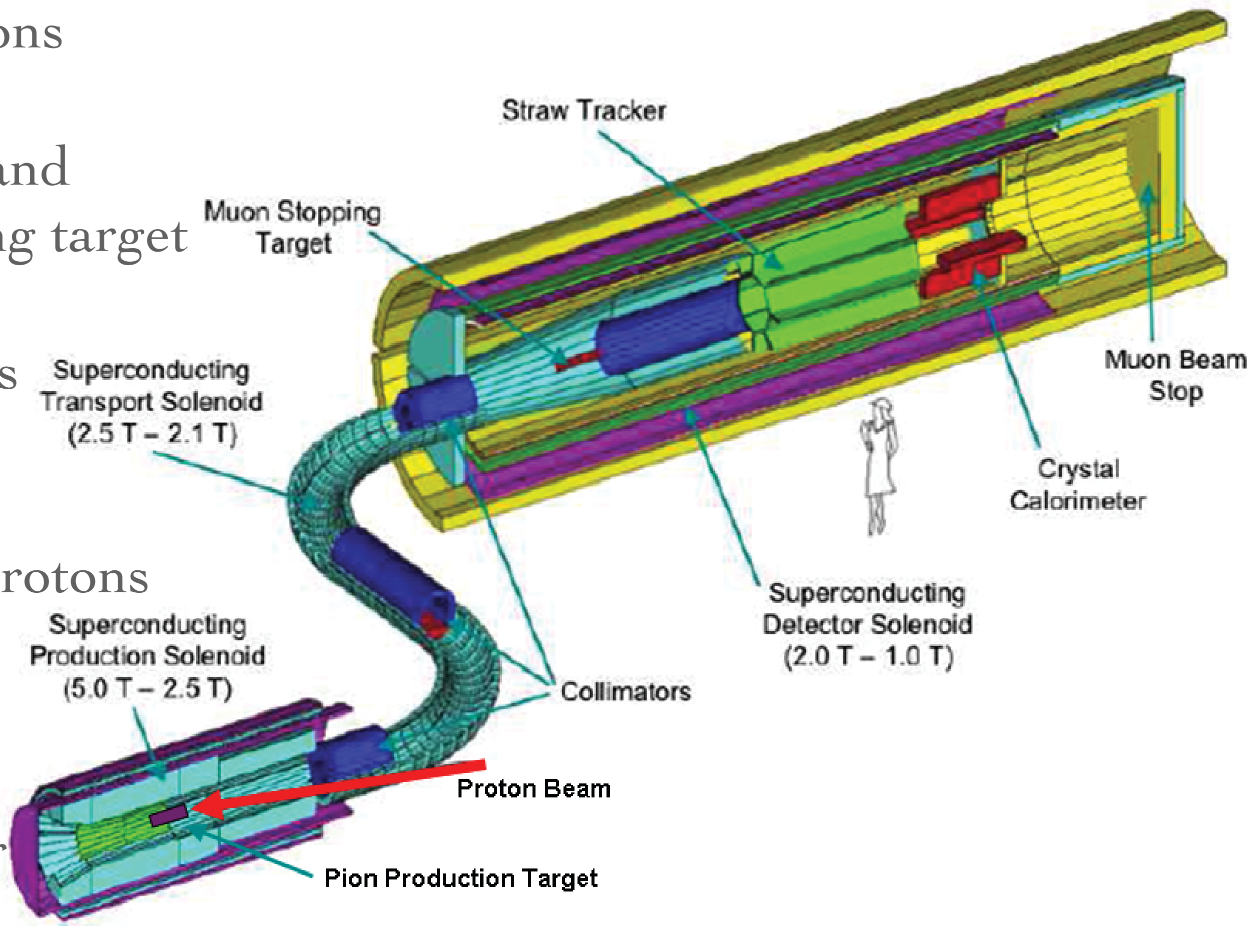
Project X Upgrades

- Ultimate sensitivity would be provided by Project X linac as proton source
  - Deliver up to 200 kW average beam current:
    - ~3 x 10^{14} protons/sec at 8 GeV (x10 previous slide)
    - 9mA, 1 msec, 5 Hz
- Three Upgrades for x10 from 200 kW to 2000 kW at 8 GeV:
  - Increase Pulse Length
  - Increase Repetition Rate
  - Increase Number of Klystrons

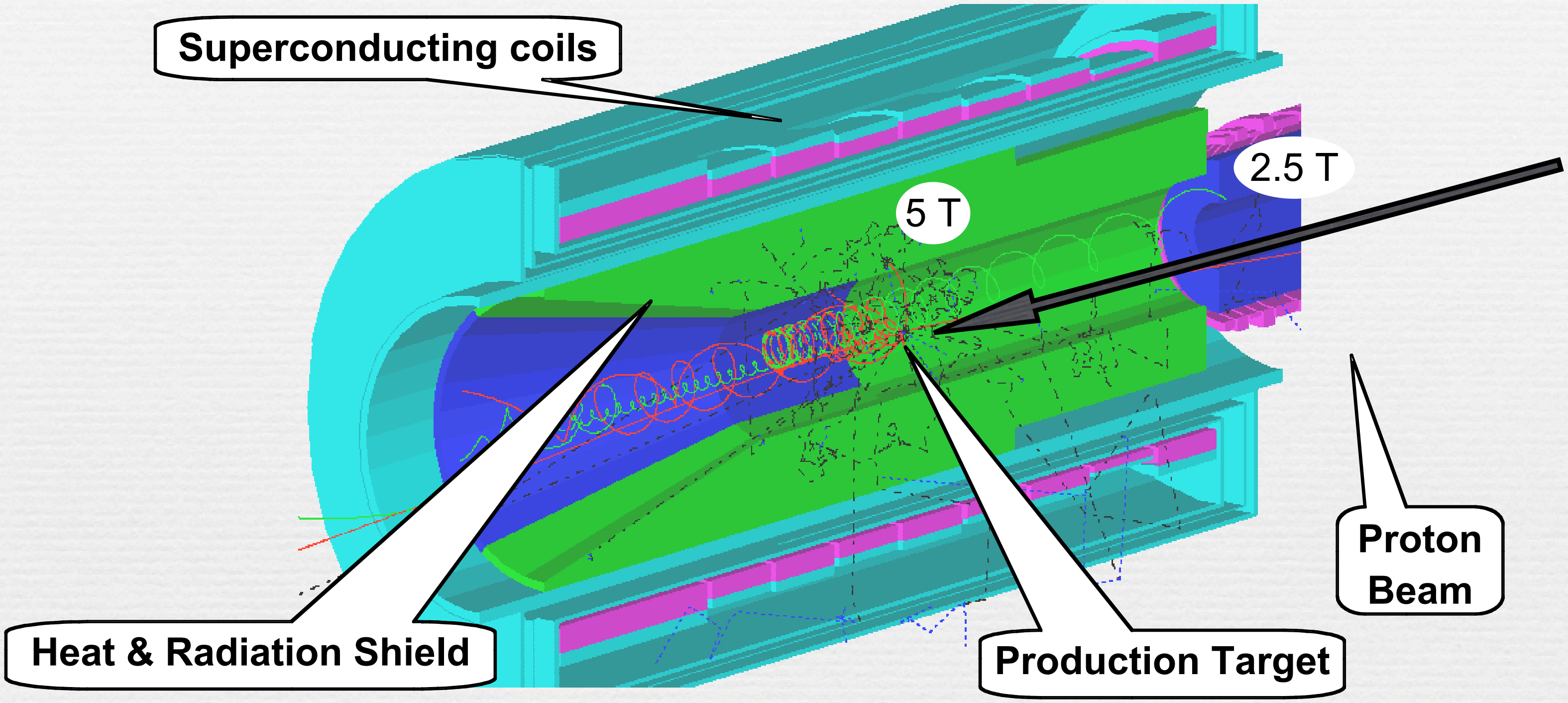
need to understand how to push single-event sensitivity to use additional capability

Overview of Experiment

- Magnetic bottle trapping backward-going pions
- Decay into muons and transport to stopping target
- “S”-curve eliminates backgrounds
- Absorbers for antiprotons
- Tracking
- Crystal Calorimeter



Production Region

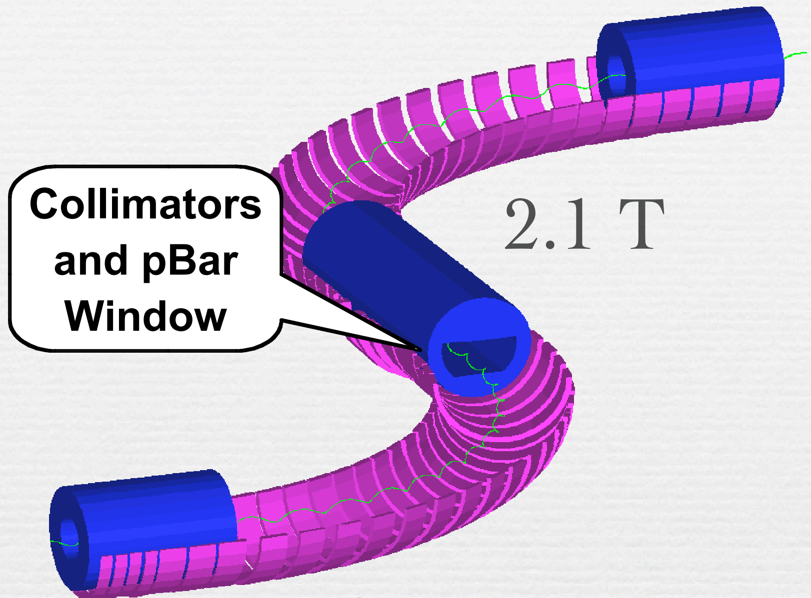


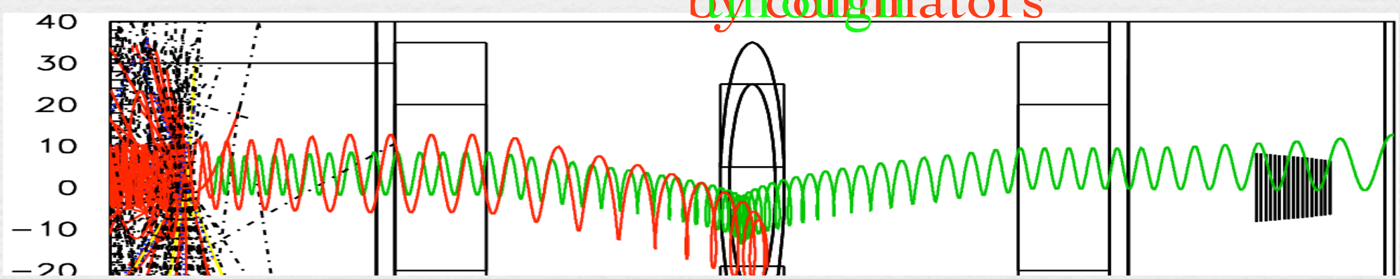
- **Axially graded 5 T solenoid captures low energy backward and reflected pions and muons, transporting them toward the stopping target**

- Cu and W heat and radiation shield protects superconducting coils from effects of 50kW primary proton beam: need upgrade from MECO design for > 50 kW

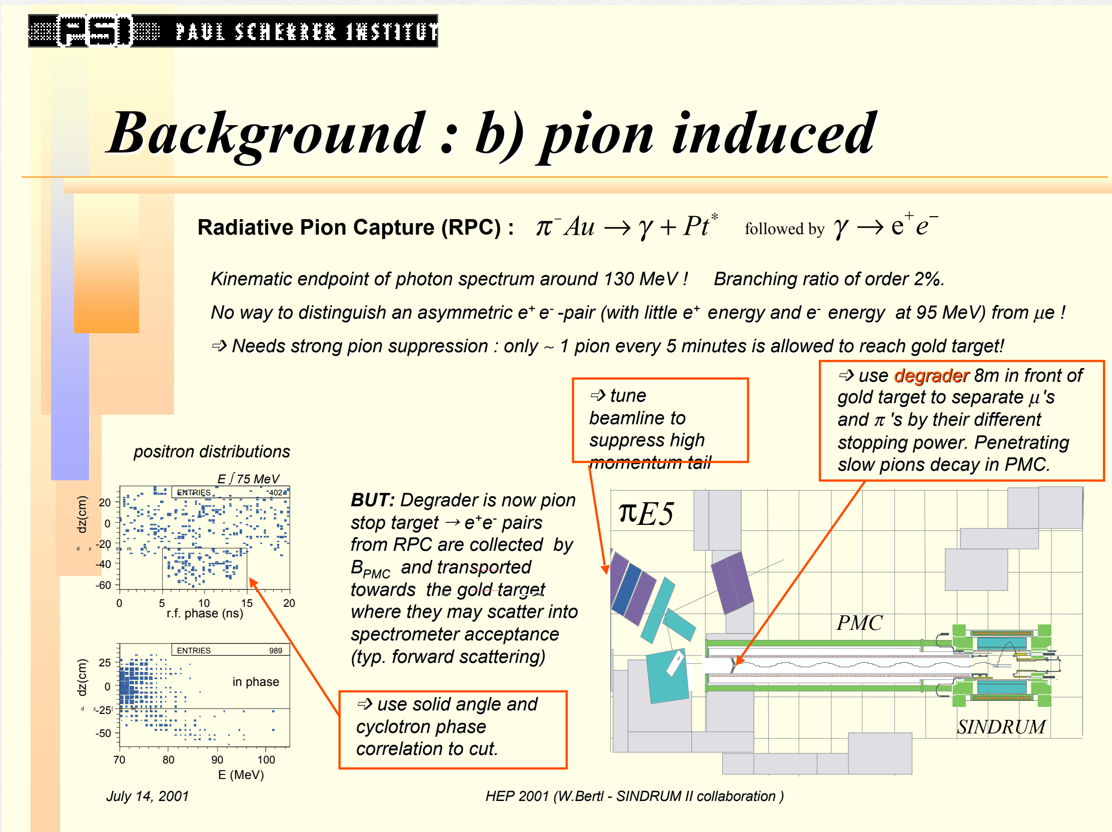
Transport Solenoid

- Curved solenoid eliminates line-of-sight transport of photons and neutrons
- Curvature drift and collimators sign and momentum select beam
- dB/ds < 0 in the straight sections to avoid trapping which would result in long transit time



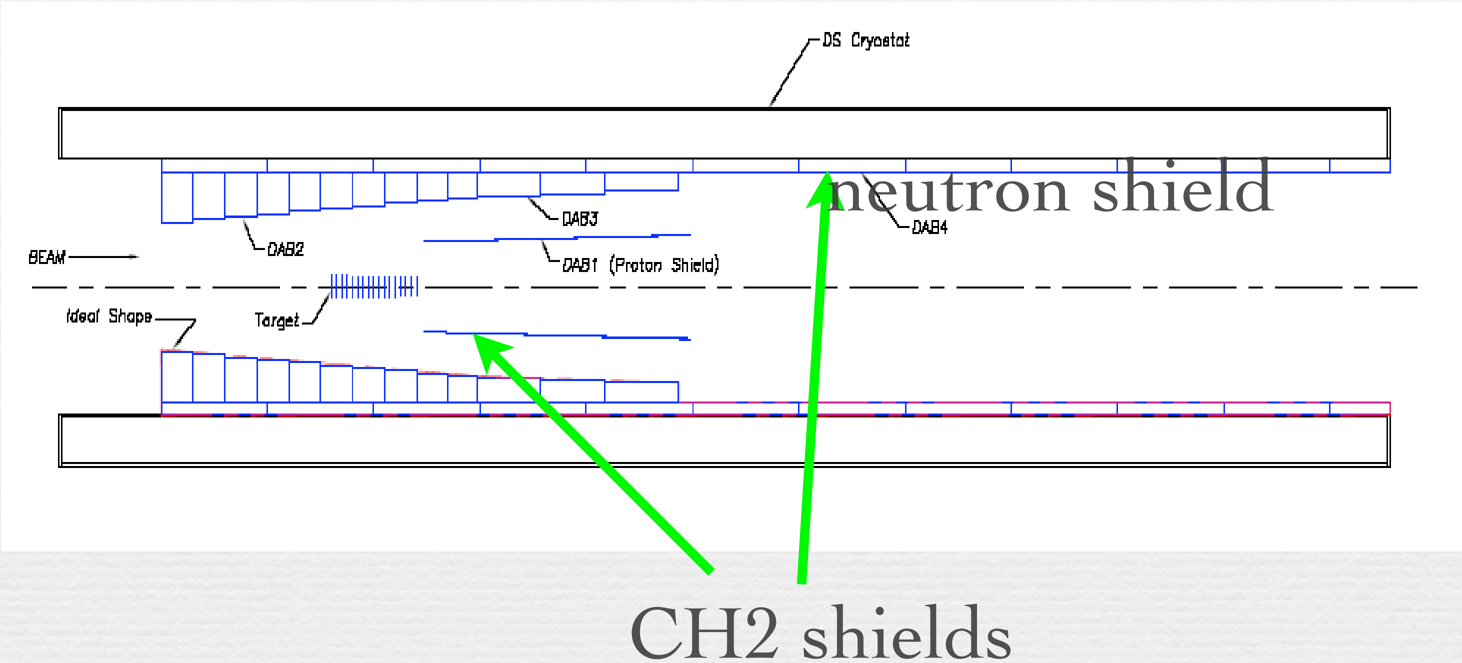


Key Improvement of Both COMET and $\mu 2e$



Curved Transport Solenoid in both modern expt's

Stopping Target Region



- Conical Shield Reduces background and high rate from protons produced in stopping target
- Outer shield absorbs neutron cloud

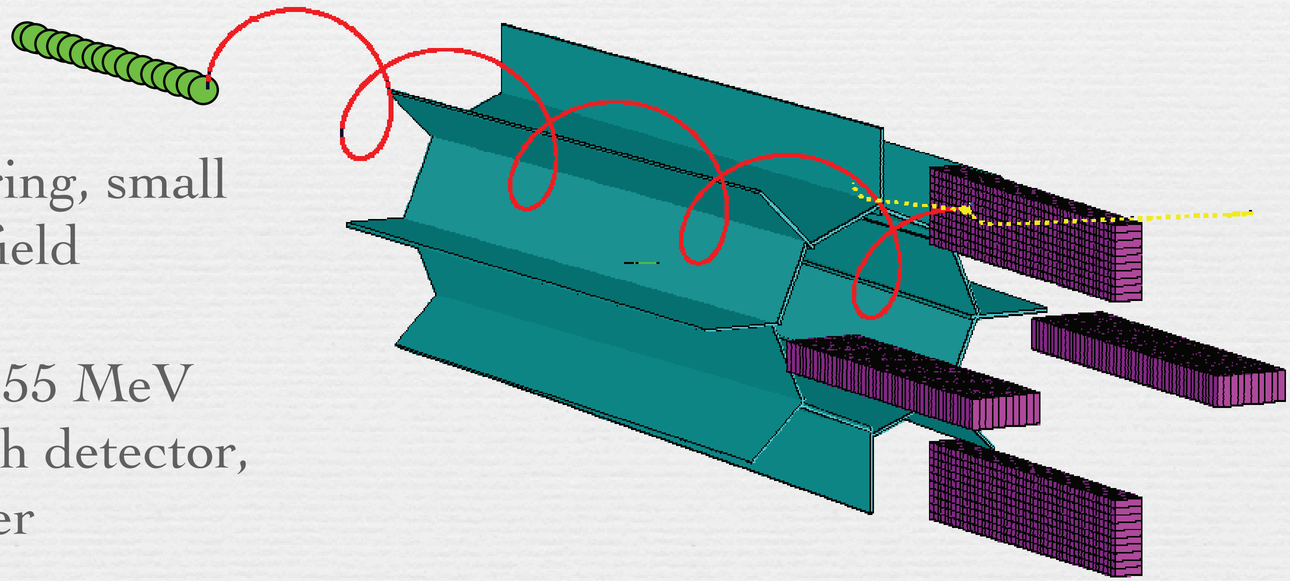
Detector

- Octagon and Vanes of Straw Tubes
- Immersed in solenoidal field, so particle follows near-helical path
  - dE/dx, scattering, small variations in field
- Particles with $p_T < 55$ MeV do not pass through detector, but down the center
- Followed by Calorimeter

σ= 200 μ transverse, 1.5 mm axially

2800 axial straw tubes, 2.6 m by 5 mm, 25μ thick

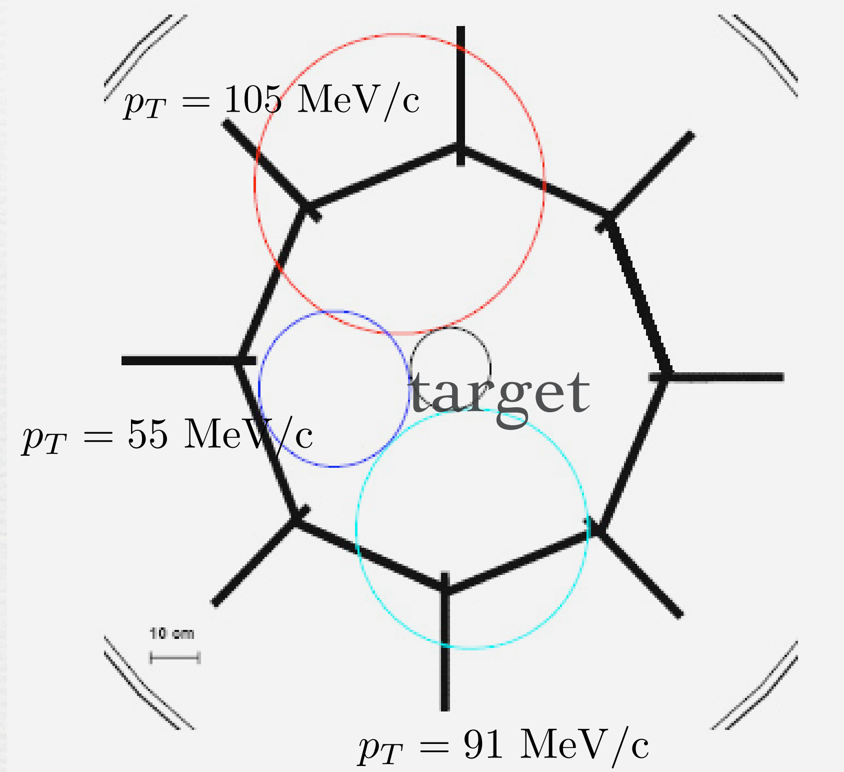
use return yoke as CR shield



σ /E = 5%, 1200 3.5 X 3.5 X 12 cm $PbWO_4$

Beam's Eye View

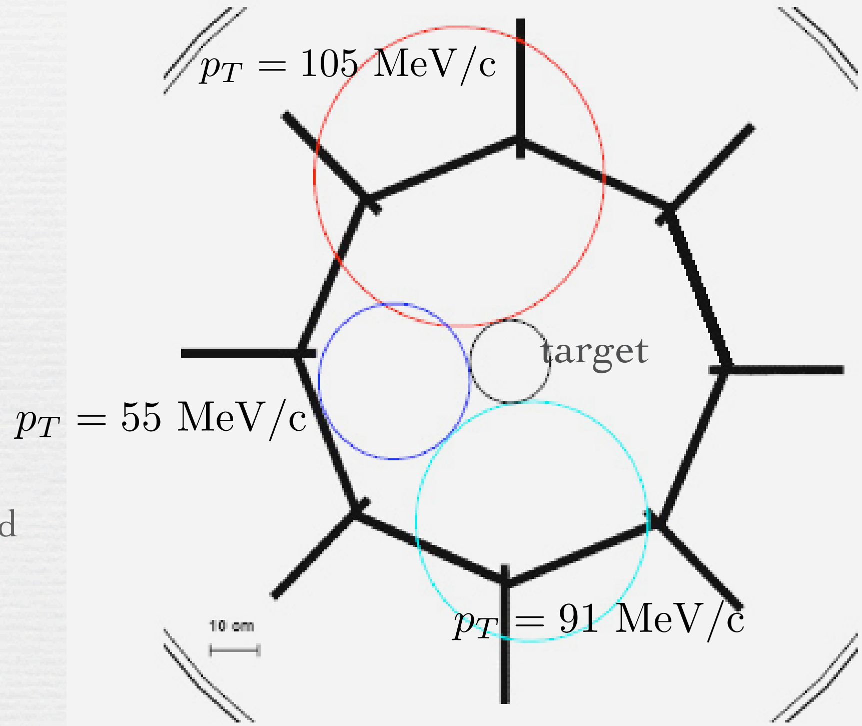
- Below p_T = 55 MeV, electron stays inside tracker and is not seen
- Looking for helix as particle propagates downstream
- More "vanes" fire as momentum increases



Note: <0.3% of e- from DIO have p_T>55 MeV/c

Details

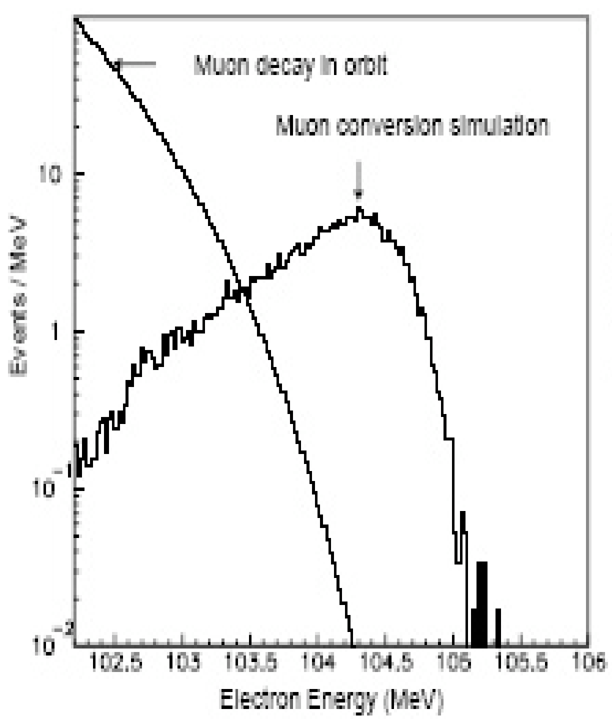
- 38 -70 cm active radius
- Geometry: Octagon with eight vanes, each ~30 cm wide x 2.6 m long
- Straws: 2.9 m length 5mm dia., 25 mm wall thickness to minimize multiple scattering – 2800 total
- Three layers per plane, outer two resistive, inner conducting
- Pads: 30 cm 5mm wide cathode strips affixed to outer straws - 16640 total pads
- Position Resolution: 0.2 mm (r,φ) X 1.5 mm (z) per hit is goal
- Energy loss and straggling in the target and multiple scattering in the chambers dominate energy resolution of 1 MeV FWHM



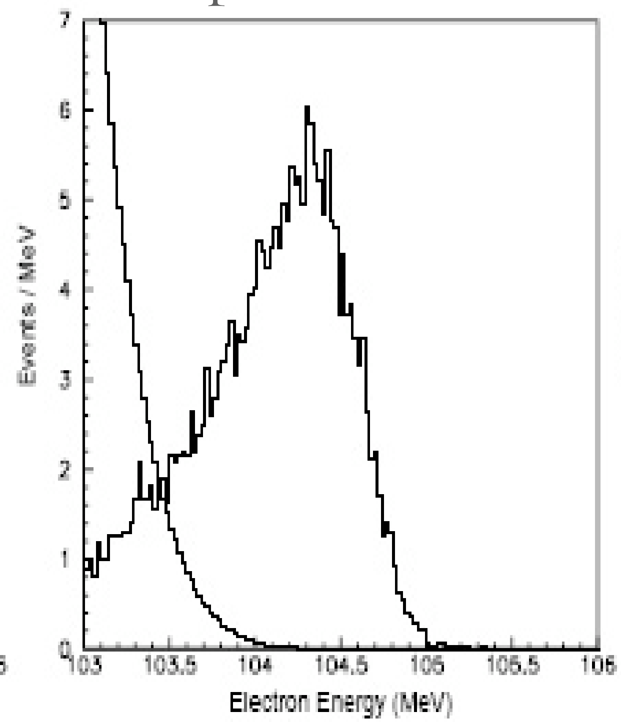
Decay-In-Orbit

- $R_{e\mu}=1\times10^{-16}$, Energy resolution 1 MeV (FWHM)

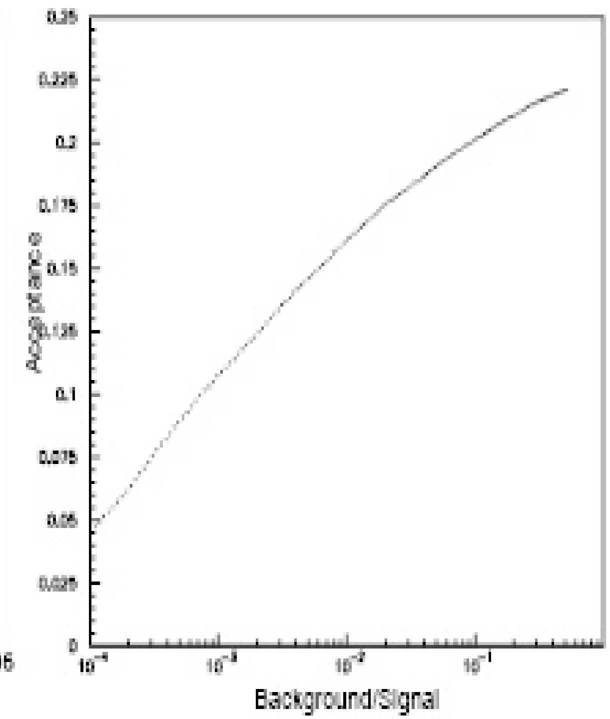
- Resolution is most important factor



Log scale



Linear scale



Acceptance and S/B as E_{thresh} varied

Other Backgrounds

- Delayed: due to beam particles which take > ~ few hundred nanoseconds before they produce signals in the detectors on average
  - Protons, neutrons, gammas from muon capture
  - Photons from radiative muon capture
- Antiproton annihilations along beam line or near target- (none in SINDRUM II, potential problem for μ2e)
- Cosmic Rays- Back/Signal proportional to (run time)/(beam intensity) (can measure off-spill)

Some of Backgrounds...

Type	Description
e_t	beam electrons
n_t	neutrons from muon capture in muon stopping target
γ_t	photons from muon capture in muon stopping target
p_t	protons from muon capture in muon stopping target
$e(DIO)_t < 55$	DIO from muon capture in muon stopping target, $<$ 55 MeV
$e(DIO)_t > 55$	DIO from muon capture in muon stopping target, $>$ 55 MeV
n_{bd}	neutrons from muon capture in beam stop
γ_{bd}	photons from muon capture in beam stop
$e(DIO)_{bd} < 55$	DIO from muon capture in beam stop, $<$ 55 MeV
$e(DIO)_{bd} > 55$	DIO from muon capture in beam stop, $>$ 55 MeV
$e(DIF)$	DIO between stopping target and beam stop

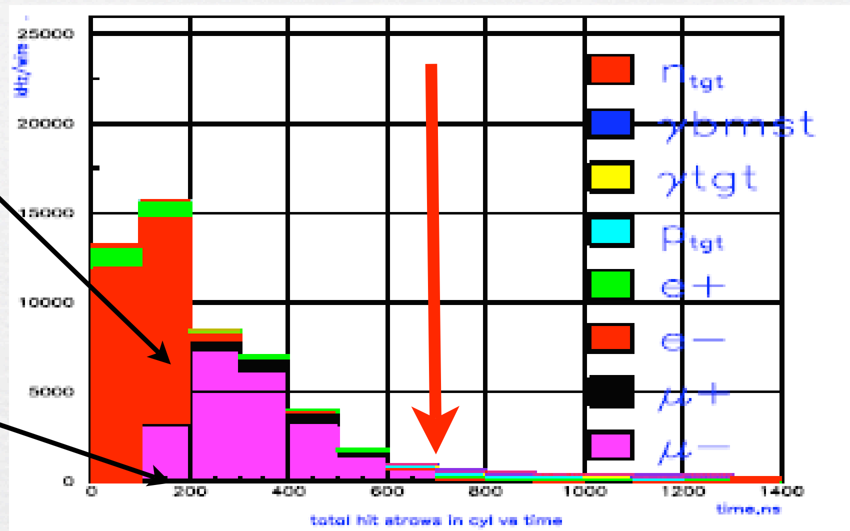
bd = albedo from beam stop

Backgrounds vs. Time

700 nsec

beam e⁻

μ DIF



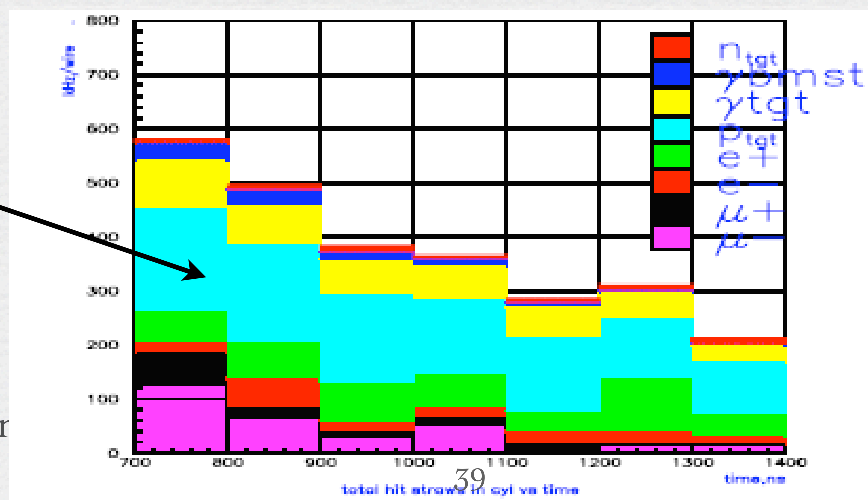
0-1400

nsec

Rate (MHz)

μ Capture

Protons



700-1400

nsec

Rate (kHz)

Measuring Background

Source	Method
Energy Resolution	$\pi^+ \rightarrow e^+ \nu_e$ with reduced field
Misreconstructed Tracks	Relax calorimeter/ track agreement
False Tracks (from extra hits)	Allow missing hits, and measure "single hit" rate

Rates In Tracker

- Rates at *Beginning* of > 700 nsec Time Window, so these are highest
- Rates are manageable

Type	Rate(Hz)	$\mathcal{P}$ hit	Mean N hits/bkg part	R_{wire} (kHz)
e_t	2.7×10^{11}	0.00032	1.54	65
n_t	2.43×10^{11}	0.000142	2.887	49
γ_t	2.43×10^{11}	0.000248	4.524	134
p_t	0.181×10^{11}	0.00362	6.263	202
$e(DIO)_t < 55$	0.795×10^{11}	9.8×10^{-5}	1.44	5.5
$e(DIO)_t > 55$	2.07×10^{8}	0.00127	22.7	2.1
n_{bd}	0.475×10^{11}	7.1×10^{-5}	5.0	5.9
γ_{bd}	0.475×10^{11}	8.3×10^{-5}	4.5	6.1
$e(DIO)_{bd} < 55$	2.1×10^{11}	8.9×10^{-5}	1.	6.6
$e(DIO)_{bd} > 55$	5.46×10^{8}	1.82×10^{-4}	1.5	0.05
$e(DIF)$	2.74×10^{6}	1	35.84	34.5
total				464

Calculating Signal Rate

Source	Factor
Running Time (sec)	1.1×10^{7}
Proton Flux (Hz)	3.6×10^{13}
μ entering transport solenoid / incident proton	0.0043
μ Stopping Probability	0.58
μ Capture Probability	0.60
Fraction of Capture in Time Window	0.49
Electron Trigger Efficiency	0.90
Geometrical Acceptance, Reconstruction, etc	0.19
Detected Events for $R_{\mu e} = 10^{-16}$	5.0

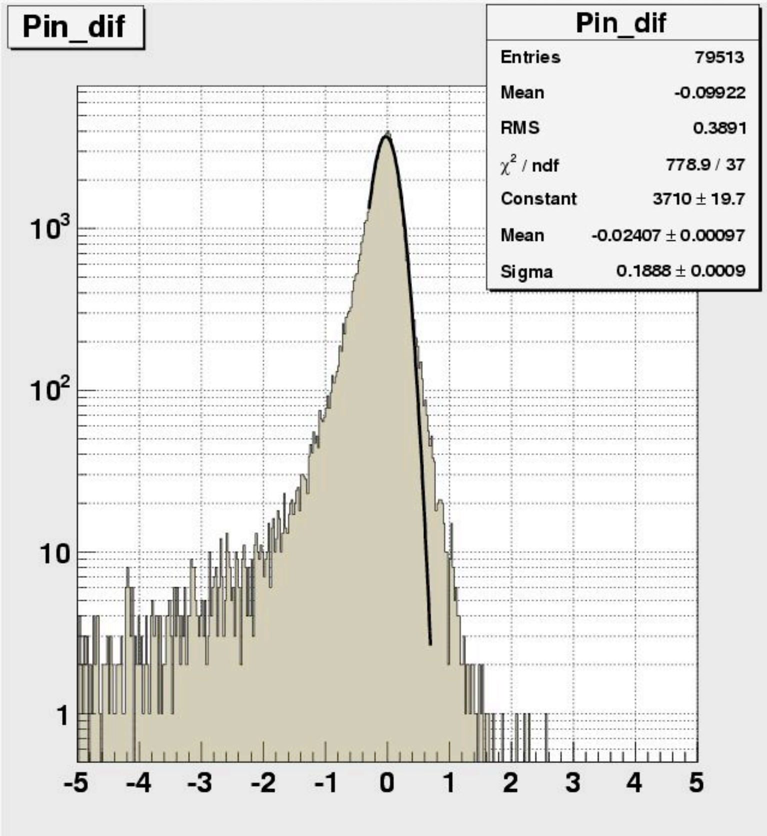
Final Backgrounds

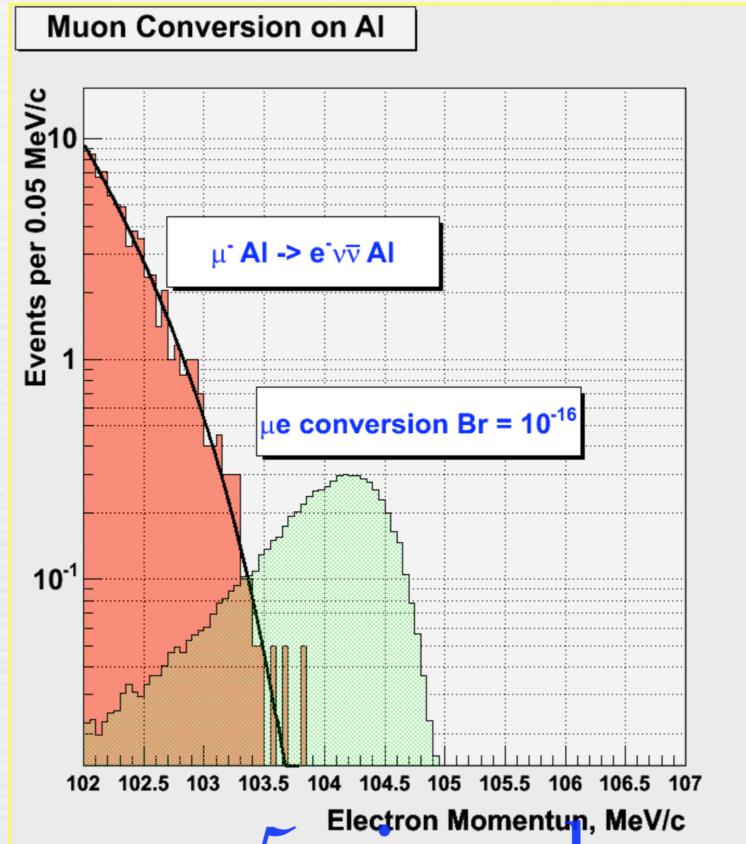
- For $R_{\mu e} = 10^{-16}$ expect 5 events to 0.5 bkg
- Extinction factor of 10^{-9}

5 signal

Source	Number/ 4×10^{20}
DIO	0.25
Radiative π capture	0.08
Scattered e^-	0.04
μ DIF	0.08
π DIF	<0.004

Summary of Capabilities





5 signal

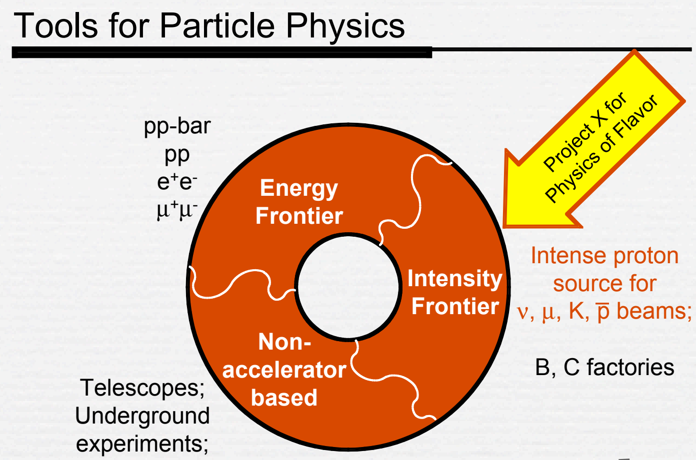
- Resolution and Sensitivity

Cost and Schedule

~$100M *~2014*

- A detailed cost estimate of the MECO experiment had been done just before it was cancelled:
  - Solenoids and cryogenics: **$58M**
  - Remainder of experimental apparatus: **$27M**
  - Additional Fermilab costs have not been worked out in detail. Recent Project X era planning exercise gives ~ $130M total cost.
- Hope to begin Accelerator work along with NOvA upgrade ~2010 (or 2011 if Run II extended)
  - Based on the original MECO proposal, we believe the experiment could be operational within five years from the start of significant funding
  - Driven by magnet construction.
- With the proposed beam delivery system, the experiment could collect the nominal 4×10^{20} protons on target in about one to two years, with no impact on NOvA

Conclusions



- **The μ2e experiment is an important measurement!**
- In the initial phase (without Project X) we would either:
  - ***Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude (${R_{\mu e}} < 6 \times 10^{-17}$ @ 90% C.L.)***
  - ***Discover unambiguous proof of Beyond Standard Model physics***
- **With a combination of Project X and/or improved muon transport, we could either**
  - Extend the limit by up to two orders of magnitude
  - Study the details of new physics